# Successes and Challenges using GPUs for Weather and Climate Models


DOE Jaguar


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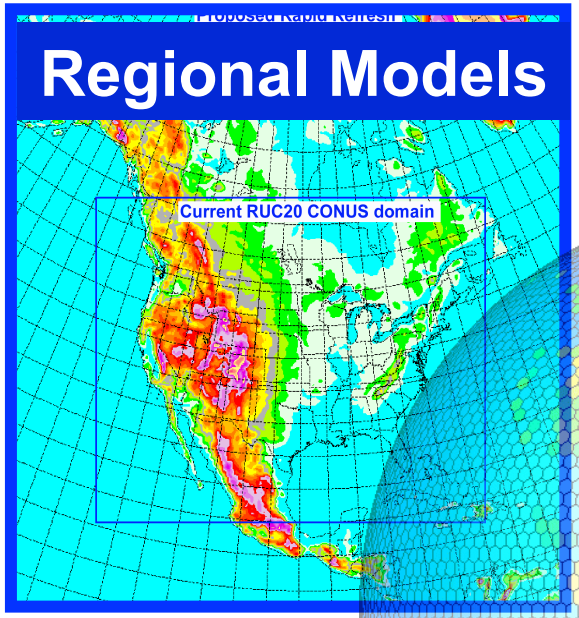
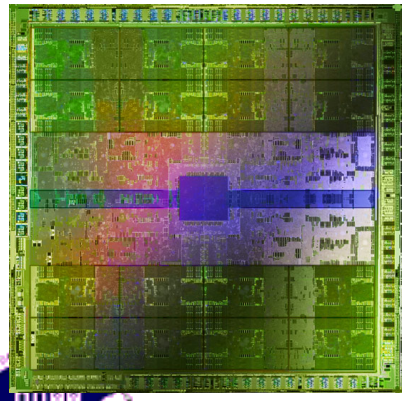
- CPU
  - Bigger Systems
  - More Expensive Facilities
  - Bigger Power Bills
  - Lower System Reliability
- GPU
  - Faster
  - Less power
  - Lower cost




# GPU Technology

- NVIDIA: Fermi chip first to support HPC
  - Formed partnerships with Cray, IBM on HPC systems
  - #1, #3 systems on TOP500 (Fermi, China)
- AMD/ATI: Primarily graphics currently
  - #7 system on TOP500 (AMD-Radeon, China)
  - Fusion chip in 2011 (5 TeraFlops)
- Intel: Many Integrated Core (2012), 32-64 cores

NVIDIA: Fermi (2010)



✧ 1.1 TeraFlops
✧ 8x increase in double precision
✧ Increase in memory bandwidth
✧ Error correcting memory

NVIDIA: Tesla (2008)





GPU: 2008
933Gflops
150W

CPU:2008
~45 Gflops
160W

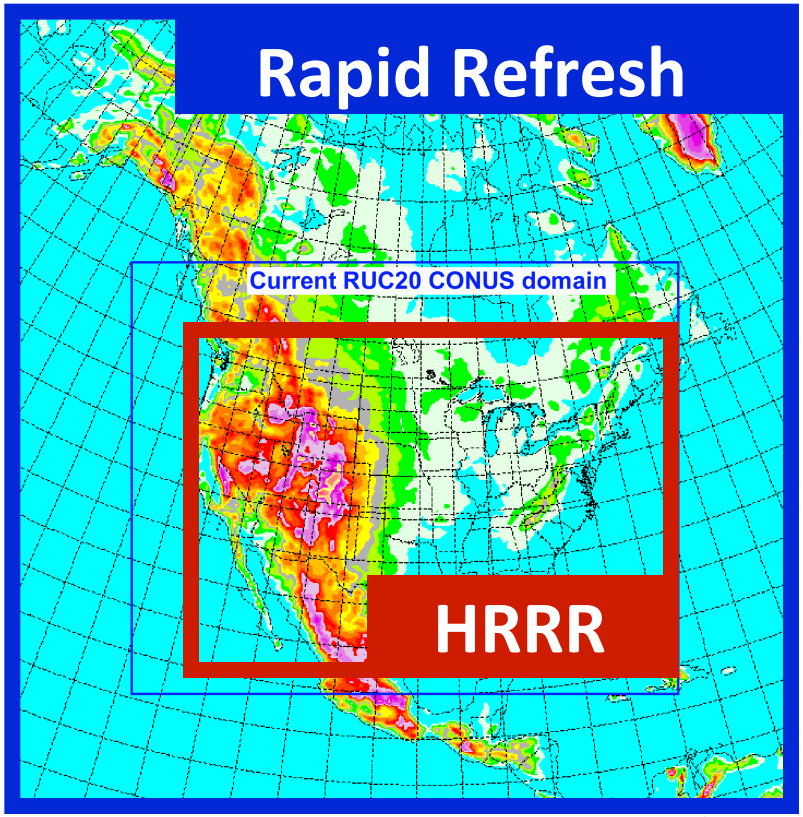
# High-Resolution Rapid Refresh

## Real-time, 12 hour forecast, 3-km CONUS domain, updated hourly

***Explicit prediction of thunderstorms***

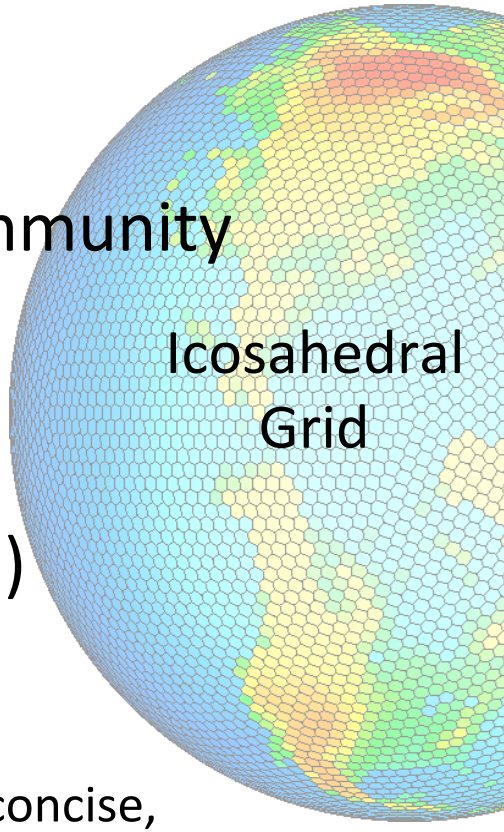
***Improved prediction of terrain related and other mesoscale features (wind, clouds, precip)***

***HRRR runs as nest within RUC or Rapid Refresh and benefits from RUC / RR data assimilation***



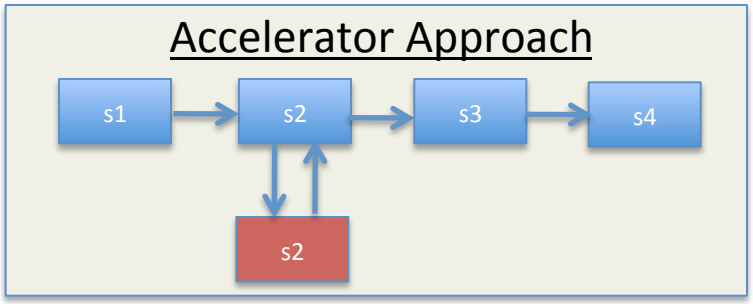
# Using GPUs for Global Cloud Resolving Models (GCRM)

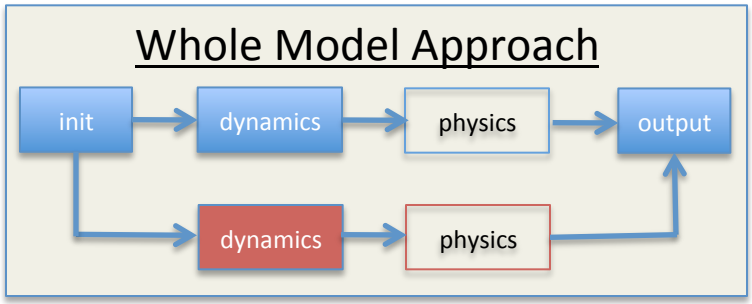
- Benefits
  - Clouds have a major influence on weather and climate
  - Improvements in 5-100 day forecasts
  - Improved Hurricane track and intensity
- Active developments in the research community
  - NICAM: University of Tokyo
  - GCRM: Colorado State University
  - NIM: NOAA Earth System Research Laboratory
- Non-hydrostatic Icosahedral Model (NIM)
  - Targeting 2KM horizontal resolution
  - Uniform, hexagonal-based, icosahedral grid
  - Novel indirect addressing scheme used that permits concise, efficient code



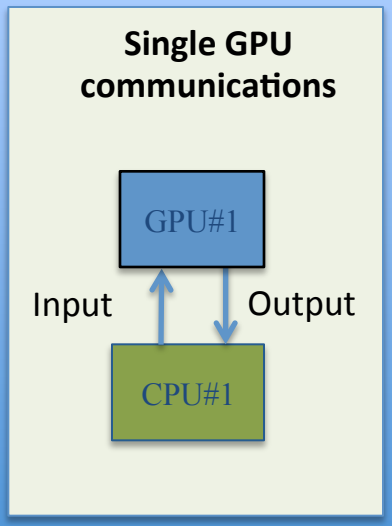
# Software Development

from CPUs to GPUs (2010s)

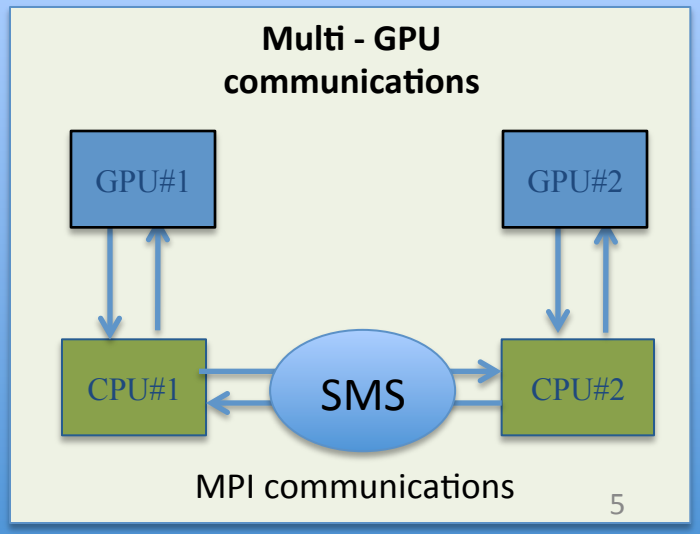



- NIM was designed for CPU and GPU Architectures
- Code converted to CUDA using the F2C-ACC compiler we developed
  - Commercial compilers were not available in 2008




- Serial Performance
  - **2009: 34x Tesla / Harpertown**
  - **2010: 20x Fermi / Nehalem**
- Parallel Performance
  - **2010: 15x with MPI communications**

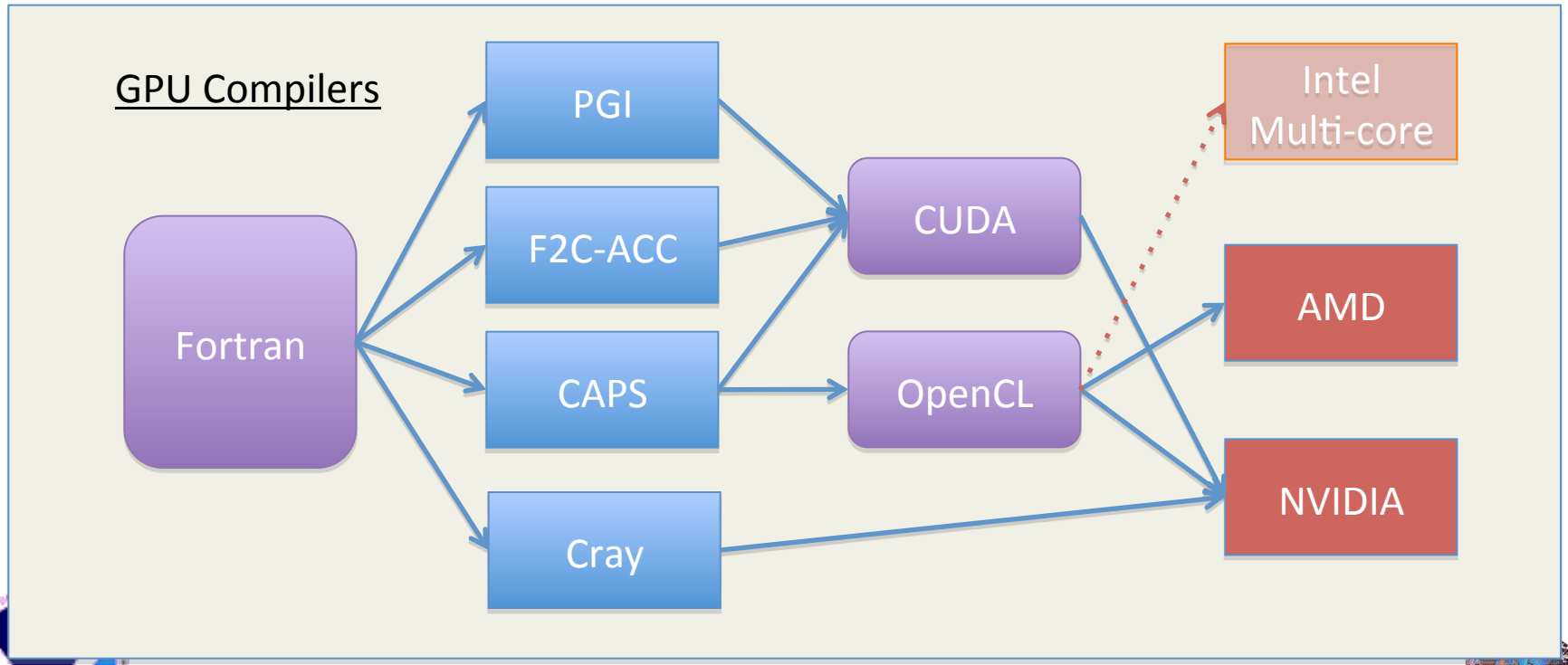


# GPU Programming Approaches

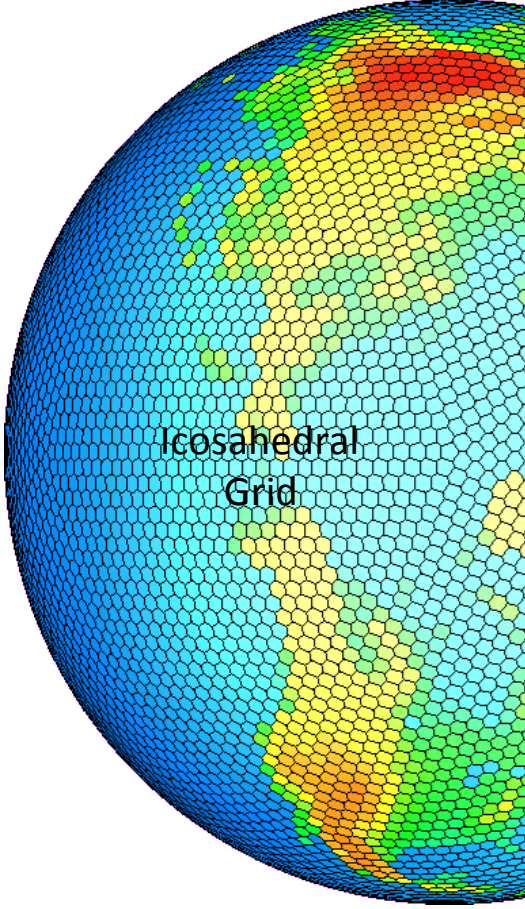
- Language Approach
  - CUDA, OpenCL, CUDA Fortran, etc.
  - User control over coding and optimizations
    - May not be portable across architectures
  - Requires that separate versions be maintained
    - In practice this rarely works – too costly, difficult
- Directive-based Approach
  - Single source for CPU, GPU, serial, parallel
  - Appear as comments in the source
    - !ACC$DO VECTOR (1)
  - Compilers can analyze and (hopefully) generate efficient code
    - Dependent on maturity


# Directive-Based Fortran GPU Compilers and Portability

- OpenACC proposed as a standard
  - PGI: Accel
  - F2C-ACC: OpenSource
  - CAPS: HMPP
  - Cray: OMP "like"

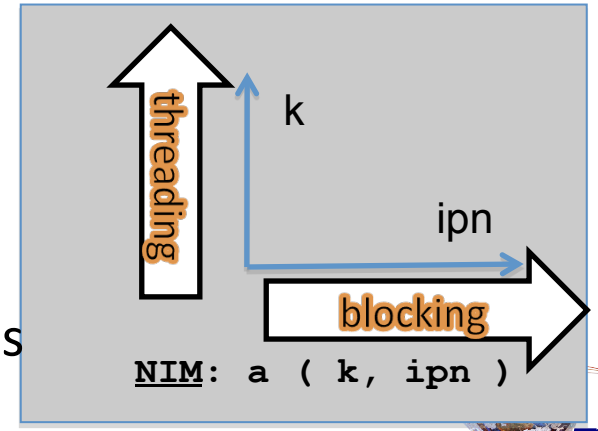


# NIM Dynamics




- Uniform, hexagonal-based, icosahedral grid
- Novel indirect addressing scheme permits concise, efficient code

- Dynamics is running entirely on GPUs
  - Horizontal data dependencies
  - 2D arrays (vertical, horizontal)
  - GPU threading across the vertical
    - 32, 96 levels increasing to 192 levels at finer scales
  - Physics (scientific) integration in progress

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# F2C-ACC GPU Compiler

- Developed to speed parallelization of NIM
  - Commercial compilers were not available in 2008
- Translates Fortran to C or CUDA
  - Many (but not all) language features supported
  - Generates readable, debuggable code with original comments retained
- Ten directives for code parallelization, eg.

| | |
|---|---|
| – ACC$REGION | ! Define GPU regions |
| – ACC$DO | ! Identify loop level parallelism |
| – ACC$DATA | ! Move data between CPU and GPU |
| – ACC$INSERT, ACC$REMOVE | ! Hand insertions / deletions where translation is not available |

- Available on request


# Fortran GPU Compiler Results (2011)

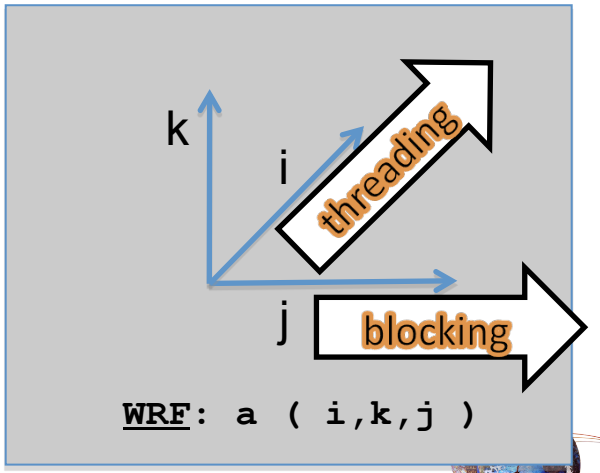
Using NIM G5 - 10242 horizontal points, 96 vertical levels
Fermi GPU vs. Intel Westmere CPU Socket

| NIM routine | CPU 1-core Time (sec) | CPU 6-core Time (sec) | F2C-ACC GPU Time (sec) | HMPP GPU Time (sec) | PGI GPU Time (sec) | F2C-ACC Speedup vs. 6-core CPU |
|---|---|---|---|---|---|---|
| Total | 8654 | 2068 | 449 | -- | -- | 4.6 |
| vdmints | 4559 | 1062 | 196 | 192 | 197 | 5.4 |
| vdmintv | 2119 | 446 | 91 | 101 | 88 | 4.9 |
| flux | 964 | 175 | 26 | 24 | 26 | 6.7 |
| vdn | 131 | 86 | 18 | 17 | 18 | 4.8 |
| diag | 389 | 74 | 42 | 33 | -- | 1.8 |
| force | 80 | 33 | 7 | 11 | 13 | 4.7 |

# WRF Physics

- Community Model used worldwide for more than a decade
  - Significant number of collaborators, contributors
- Used in WRF-ARW, WRF-NMM, WRF-RR, WRF-CHEM, HWRF, etc.
- Traditional cartesian grid
  - 3D arrays (horizontal, vertical, horizontal) ==> `array3D( i,k,j )`
- Designed for CPU architectures
- **Limited ability to change the code**
  - **Must continue to be performance portable**

- GPU parallelization
  - In progress – select routines
  - Dependencies in vertical
  - GPU: threading in horizontal dimensions
  - Collapse I, j dimensions during transpose

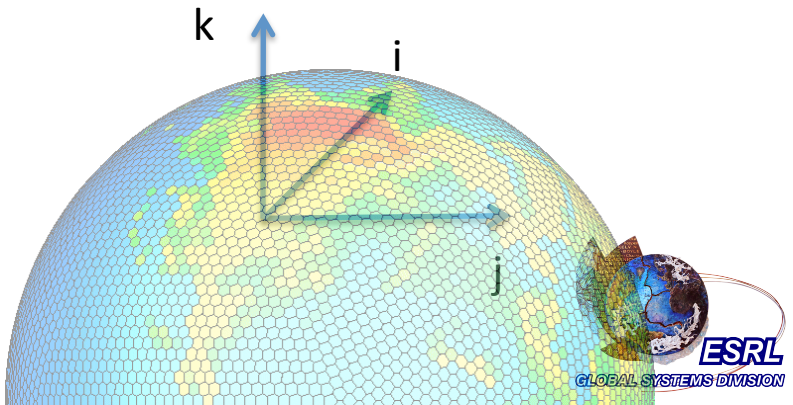


# Parallelization Factors for NIM

- Code design a dominant factor in performance
  - Weather codes typically have a high memory access to compute ratio
    - Implies lots of accesses, few computations
  - Data alignment led to a 10x improvement
- Data dependencies guide parallelization
  - Dynamics are in the horizontal
    - a [ vert, horiz ]
  - Physics are in the vertical column
    - a [ horiz , vert ]
  - Transpose needed to optimize memory accesses

```
lat-lon a ( k, i, j )

NIM:     a [ k, indx)
```



# Successes

- Parallelization of NIM
  - 5x speedup of NIM dynamics (socket-to-socket)
  - F2C-ACC continues to be used for NIM
- Development of F2C-ACC
  - **Useful for comparisons to commercial compilers**
    - **Establish performance benchmarks**
    - **Ease of use: readability of generated code**
    - **Directives that support our weather, climate codes**
    - **Validate correctness of results**
  - Feedback to compiler vendors
    - Communicate needs in the weather and climate community


# Challenges

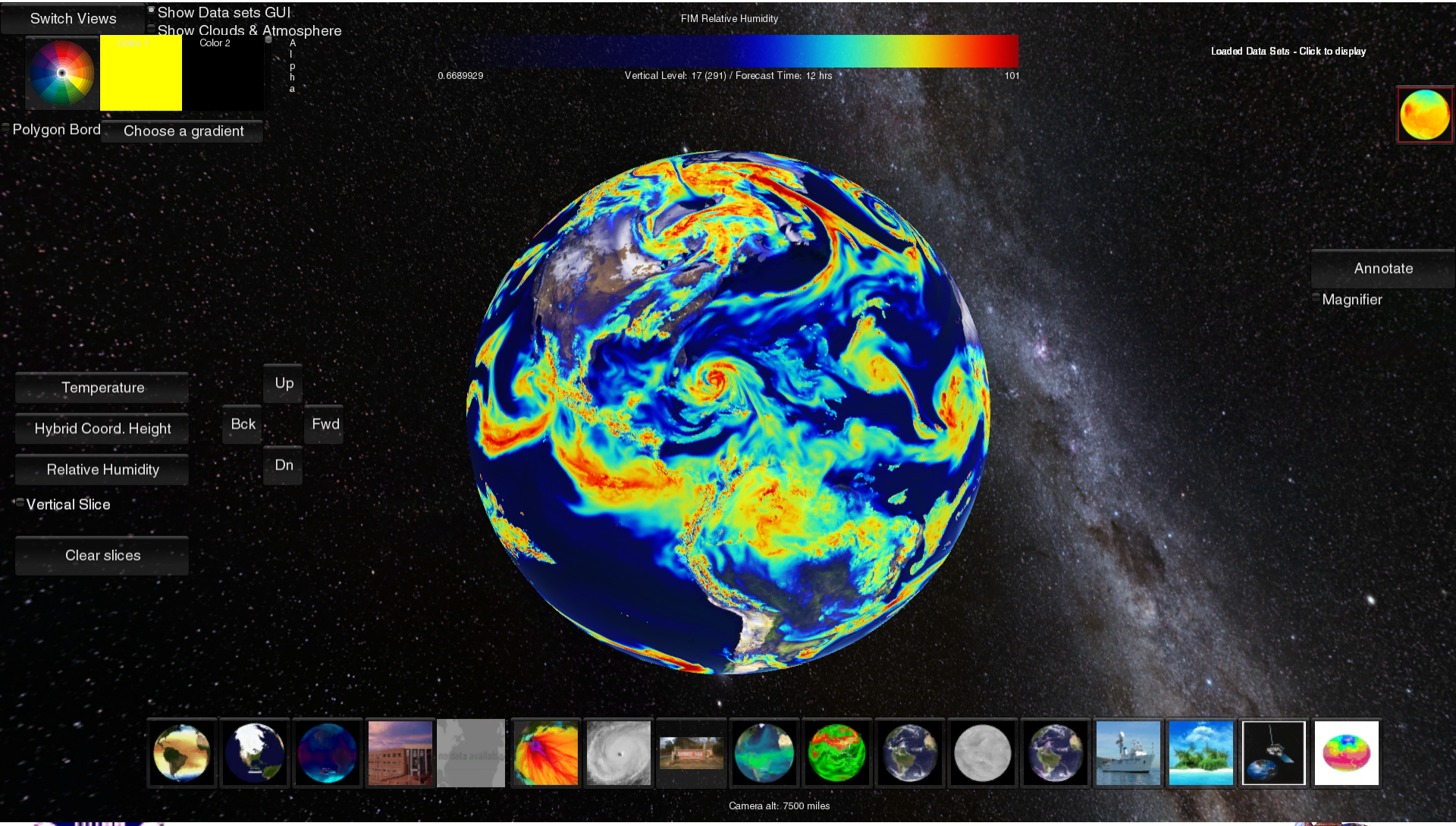
- Validating results
  - dependent on the computer architecture
    - CPU, GPU, Intel, IBM, NVIDIA, AMDm etyc
  - Physics is more sensitive than dynamics
  - How do you determine acceptable results?
- Performance portability
  - Modest to extensive code changes
  - Promotion of variables for correctness
    - Demotion of variables for performance
  - Loop restructuring
  - Blocking and threading control


# Challenges

- Data management
  - How to work with high data volume
    - 15 KM, 2M horizontal points, 96 vertical
      - 2GB per variable per output time
    - 1.75KM, 167M horizontal points, 192 vertical
      - Projected 64GB per variable per output time
- Visualization
  - Exploring using gaming software
    - GPUs, progressive disclosure

UNITY 3D
game development tool

# TerraViz

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# Conclusion

- Committed to a single source
  - Performance portable between CPU, GPU, serial, parallel
    - NVIDIA, AMD, Intel, etc
  - We anticipate significant challenges for legacy codes
- We will continue to compare compilers
  - F2C-ACC, HMPP, and PGI Accel
    - Performance, ease-of-use
- Challenges Remain
  - Codes take too long to port to GPUs
  - Performance portability a concern
  - Standards for GPU directives